PLANT NUTRITION BETWEEN PROBLEMS OF ACCESS AND PROBLEMS OF EXCESS: SAFETY NET FILTER FUNCTIONS

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Abstrak

Keberlanjutan suatu sistem pertanian tergantung pada kemampuan petani untuk mempertahankan produktivitas tanah, mencegah kemarahan tetangga, menyenangkan konsumen dan membuat kesepakatan dengan birokrasi yang berusaha mengontrol kehidupan petani. Karena issu mengenai kebutuhan hara tanaman pada umumnya ditentukan oleh masyarakat, muncullah pendekatan baru yang mendasari pemahaman akan pemanfaatan hara yang efisien dalam proses tanah-tanaman untuk menghindari kelebihan hara yang pada umumnya ditemukan di daerah beriklim sedang dan memanfaatkannya sebaik mungkin pada kondisi ketersediaan hara rendah yang umumnya terdapat di daerah tropik. Tantangan dalam bidang hara tanaman terutama terletak pada usaha memperlebar rentang kondisi kelebihan dan kekurangan hara, daripada usaha menentukan satu titik optimum secara ekonomi. Dua pendekatan dibahas untuk memperlebar rentang tersebut: 1) penyempurnaan teknik pengelolaan pertanian secara tepat, dan 2) pendekatan analog ekologi yang didasarkan pada fungsi filter dan manfaat pendukung dari berbagai komponen dalam sistem yang lebih kompleks, termasuk agroforestri dan tumpangsari, karena sistem ini mungkin merupakan sebagian jawaban terhadap situasi kelebihan dan kekurangan. Simulasi dengan model WaNuLCAS untuk memahami konsep jaring penyelamat hara oleh pohon berperakaran dalam, menunjukkan adanya peluang (walaupun terbatas) tertahannya hara yang tercuci ke luar dari sistem, dan dengan demikian meningkatkan efisiensi penggunaan hara pada sistem tersebut.

Abstract

Agro-ecosystem sustainability depends on the ability of farmers to maintain soil productivity, avoid angry neighbours, keep customers happy and deal with the regulatory bureaucrats that try to control their activity. As plant nutrition issues are redefined by society, new applications emerge for a basic understanding of nutrient use efficiency in soil-plant processes to avoid excess on rich soils as commonly found in the temperate zone and make the best of it under access-limited conditions common in the tropics. The main challenge of plant nutrition may be to increase the width of the domain between the access and excess frontiers, rather than to define a single 'economic optimum' point. Two approaches are discussed to widen this domain: the technical paradigm of precision farming and the ecological analogue approach based on filter functions and complementarity of components in mixed plant systems. Current understanding of plant nutrition, largely focused on monocultural situations, needs to be augmented by the interactions that occur in more complex systems, including agroforestry and intercropping as these may form part of the answer in both the excess and shortage type of situation. Simulations with the WaNuLCAS model to explore the

concepts of a 'safety-net' for mobile nutrients by deep rooted plants suggested a limited but real opportunity to intercept nutrients on their way out of the system and thus increase nutrient use-efficiency at the system level.

1. Introduction: Threats to Sustainability

Sustainability of farming and thus of agro-ecosystems depends on the ability of farmers to overcome current and future threats to a continuation of their enterprise in some form or other. These threats can derive from loss of on-site productivity, from ‘angry neighbours’ who no longer accept the lateral flows through air or water of elements and pesticides coming from the farm, from ‘worried customers’ who do not trust the quality of the products or don’t agree with the production conditions, or from ‘regulatory bureaucrats’ in a policy frame that tries to control the activity of farmers. Plant nutrition research has traditionally focused on the first of these threats, and has helped to develop plant and soil management schemes that provide for adequate nutrient supply to the current crop without unduly mining soil resources. A build-up of soil nutrient stocks, some not directly available to common crops, was seen as an unavoidable side-effect of improved crop nutrition and use efficiencies of 30-40% for N characterize the main grain production systems of the world. The apparent success of this type of plant nutrition in the intensively used agricultural lands of the temperate zone, as well as in specific areas in the tropics, has given rise to increased fluxes into the environment and thus to the *angry neighbour*, *worried customer* and *regulatory bureaucrat* type of threat to sustainability of current farming styles (Fig. 1). To support the ‘agility’ of farmers to respond to these threats, efforts to increase nutrient use efficiency at field, farm and regional scale are needed. Where part of the initial success of growth-stimulating plant nutrition was based on a largely empirical approach, exploration of the upper limits and management of the excess situation need a more precise quantitative understanding of the soil-plant-environment relationship in heterogeneous fields.

In contrast to the problems of excess nutrition, in substantial parts of the tropics the lack of adequate supply of plant nutrients remains a major constraint to crop growth. Lack of knowledge of plant nutrition, however, is not the major determinant of this situation. Fertiliser sources are generally used wherever they are financially feasible for the types of crops farmers grow, and relative prices of nutrient sources, labour and harvestable products explain most of the situations where soil fertility remains the main constraint to agricultural production for subsistence crops. Real impact on farmer’s livelihood options in these circumstances is likely to come from economical and policy changes rather than from technical options for plant nutrition per se (Izac and Sanchez, 2001).

Threats to sustainable farming globally thus consist of on-farm concerns for the nutrient balance (Access problems), angry neighbours and worried or dissatisfied customers (Excess problems) and regulations and policies that are supposed to guide between the scylla and charibdis of access and excess problems, but that not necessarily give the right signals and incentives to farmers navigating their boats in between. Research can help to define and shift the two main frontiers, but should also focus on how to increase the width of the domain in between not least to reduce economic and environmental risks (Table 1).

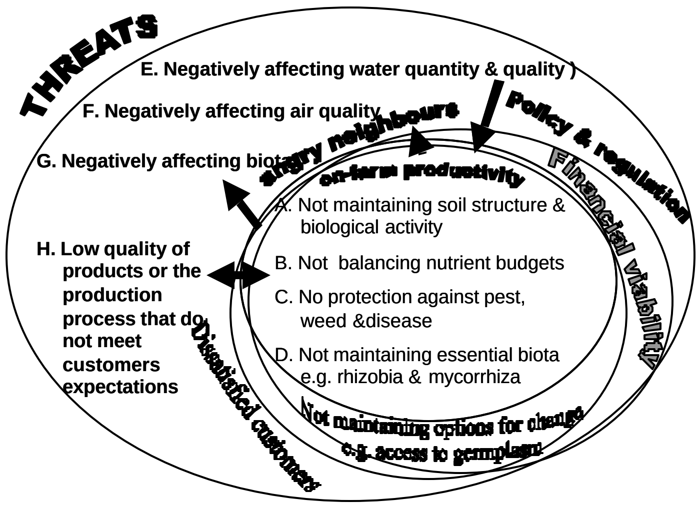

Figure 1. Threats to agricultural sustainability: the inner circle is essentially agronomic and the outer circle is more fo cused on environment and market issues.

2. Technical Control and Ecological Analogue Approaches

Two paradigms are currently used to decrease the conflicts between access and excess problems: the ***technical control*** paradigm of precision farming and hydroponics, and the ***ecological analogue*** paradigm of increased buffering and resilience. The two paradigms are not mutually exclusive, but they suggest different interventions into the status quo. Precision farming (Robert, 2001) differentiates farm operations including fertilization within a field and thus creates smaller management units to get a better tuning of supply to demand. The terminology of precision farming originated in the large fields of the US, imposed on a landscape without respect for underlying soil variability and thus highly heterogeneous, and is based on new information processing opportunities in mechanized farming There is growing recognition that the small scale tropical farmer, on fields developed organically in the landscape has in fact also been making such site-specific management decisions that characterize precision farming (Sinclair and Walker, 1998; Berkes et al., 2000). Unfortunately, plant nutrition research for the tropics has largely resulted in blanket fertilizer recommendation schemes for the tropics and ill-adapted innovations rather than supporting the decisions farmers have to make in the real, heterogeneous world, and this probably contributes to the low overall nutrient use efficiencies of farming. The efficiency of fertilizer and organic input use varies with method of application, but farmer incentives to the use of techniques that increase fertilizer use efficiency critically depend on fertilizer price (Van Noordwijk and Scholten, 1994).

Table 1. Determinants of the frontiers between the access problem, balanced nutrition and excess problem domains at different scales in plant nutrition.

Scale	Access sufficiency frontier	OK range	Excess avoidance frontier
Root	Zero-sink diffusion delivery to root, despite all rhizosphere modifications, is less than demand	Effective demand-based regulation of uptake and rhizosphere modification	Incomplete tolerance to concentration build up if mass flow delivery to root surface exceeds uptake concentration
Plant	Compensatory root development unable to reduce demand per unit root relative to available supply conditions	Internal buffer and elastic response in root development and function can achieve adequate supply of all nutrients required at any phase of plant development	Limited internal storage of excess elements in harmless forms to reduce accumulation around roots
Field – crop season	Patches with smallest supply per unit demand cause unacceptable yield shortfalls	Spatial variability in supply matches that of demand within the management unit (field or part thereof)	Patches with highest supply per unit demand cause lateral (and vertical) flows exceeding tolerance of neighbours
Field - long term	Total input is less than use + *unavoidable* losses	Balancing the nutrient budget at field scale	Total input exceeds use + *tolerable* losses
Farm	Nutrient export in farm produce and unavoidable losses occur at less than (risk-adjusted, discounted) replacement costs of nutrients	Internal waste recycling and efficient application strategies increases domain where marginal benefits exceed marginal costs of nutrient use for profitable crops	Uncontrollable inputs derived from lateral flows exceed use + tolerable losses; *tolerable* losses smaller than *unavoidable* ones
Human food chain	Food of adequate quality and nutrient ratios is not available to, or affordable by part of human population	Sufficient choice for balanced diets at affordable consumer prices	Contaminant levels and nutrient ratios in food supply exceed safety limits
Society	Limited stocks of exploitable nutrients; lack of economic incentives for nutrient recapitalization and balancing nutrient budgets on farms; cheap imports in free market trade	Adequate regulation and economic incentives for nutrient chain managers	Lack of economic incentives for recycling and use of nutrient rich waste products in whole nutrient (food) chain; lack of accounting for environmental costs

In hydroponics, the low predictability of variable soils is replaced in a more radical way by a system that allows for better technical control of supply and monitoring of demand in systems with a low buffer capacity and rapid response to management interventions. Both of these technical approaches (precision farming and hydroponics) aim to reduce variability in space and time and tend to minimize the use of organic inputs (e.g. manures, plant residues, compost, etc.) because of their less predictable composition and nutrient supply dynamics (although there have been recent advances in databases and decision support systems that facilitate the use of organic materials).

The ecological analogue approach, in contrast, accepts variability of supply and demand and the absence of full synchrony between nutrient supply and plant demand as facts of life and tries to reduce their consequences. Specifically for nutrients, this may involve the use of 'safetynets' and filter strips to mop up leftover nutrients leaving the system. The terms 'safetynets' and 'filter' are used here in a generic sense of anything that can intercept a vertical or lateral resource flow. These efforts may require an increase in (manageable) complexity by intercropping and agroforestry and an increase in the internal (organic) buffer and soil nutrient capital.

The use of a biological safety net in the form of filter strips at field boundaries has been suggested in the temperate zone as one of the options for combining environmental standards and economically feasible production, returning some complexity to landscapes dominated by monocultures. Some of the principles of more complex agro-ecosystems of the tropics may indeed be of value in the temperate, intensive agricultural world as well, as they may offer options to filter excess nutrients before they reach the neighbours' water or air, and can provide the visual attractiveness that consumers appreciate.

3. Safetynets in Sequential and Simultaneous Systems

3.1 Concepts

The concept of deep nutrient uptake by trees has been discussed for more than a century, but only applies to soils that have appreciable nutrient stocks derived from weathering or subsurface lateral flows. For nutrients of low mobility, long time frames apply and a low efficiency of uptake on a yearly time scale can still lead to appreciable depletion over the life time of a perennial crop or tree. For mobile nutrients, however, the residence time of nutrients in the subsoil is limited, and interception by trees or other deep-rooted vegetation has to occur while nutrients are on their way out of the reach of the root system or the soil system. For such situations the term 'safetynet' has been coined. Key questions on the way safetynets and filters function in natural resource management are:

- How effective are different types of filters for intercepting flows as can be expected in different rainfall regimes for nutrients differently sorbed and buffered by the soil?

- How does the filter or safety net efficiency depend on the 'mesh size' as determined by root length density and thickness of the soil layer involved?
- How quickly will filters saturate under high inflows?
- How fast can the filters regenerate between events?
- Do filters have a direct value and can they be treated as a separate 'land use practice'?
- How effectively can intercepted nutrients be-reused in the systems?

A first theoretical analysis of safetynets by Van Noordwijk (1989) showed that a limited window of opportunities exist in a sequential system for a deep-rooted fallow to intercept nutrients leached beyond the shallow crop root zone in cropping years. As argued by Sommer *et al.* (2001), nitrate sorption in subsoil can slow down nitrate movement to increase the chances of recapture by subsequent fallow vegetation although its effectiveness is limited (Suprayogo *et al.,* 2002). Subsoil nitrate sorption is common in acid tropical soils (Suprayogo *et al.,* 2002, Wong *et al.* 1990).

For nutrients of higher mobility a more permanent presence of a safetynet is required. Cadisch *et al*. (1997) and Rowe *et al.* (1999) have explored how such a safetynet function may depend on tree root length density in the layer underneath the crop root zone and provided evidence from ^{15}N placement experiments that uptake from deeper layers can be substantial, provided aboveground 'demand' exists. Again, a simulation model that looks at the interactions between leaching rates, aboveground demand, N_2 fixation and the possibilities for uptake from various parts of the soil profile is needed to move beyond qualitative statements. Rowe *et al.* (1999) calculated for hedgerow intercropping experiments in Lampung (Indonesia) that the non-N fixing tree *Peltophorum dasyrrachis* recycled 42 kg N ha^{-1} $year^{-1}$ by uptake from below the crop root zone, while the N-fixing *Gliricidia sepium* recycled only 21 kg N ha^{-1} $year^{-1}$.

The WaNuLCAS (water, nutrient and light capture in agroforestry systems) model (Van Noordwijk and Lusiana, 1999, 2000; *http://www.icraf.cgiar.org/sea/AgroModels*) describes plant-plant interaction in above- and belowground aspects. Competition and complementarity in use of nitrogen, phosphorus and water can be evaluated in the model for any combination of trees, crops, planting times, organic and inorganic input regimes, provided that basic properties of the root system and aboveground growth are known for the given soil and climate. The WaNuLCAS model incorporates key aspects of space (4 soil layers in 4 lateral zones), time (daily time steps, simulations up to 25 years or beyondg), complexity (1 - 3 tree species can be grown simultaneously, crop calendar can be specified for each zone separately) and management (fertilization, organic inputs from outside or inside the system, aboveground tree management by pruning, manipulation of root distribution) of agroforestry.

For the current exploration of safetynet functions a default parametrization was used that reflects the BMSF site in Lampung (Sumatra, Indonesia) where model validation tests were carried out focusing on deep N uptake (Rowe, 1999; Suprayogo, 2000).

3.2 Safetynet Efficiency: Effect of Rainfall

In a series of simulations that excluded P limitations on crop or tree growth, a gradual shift from water to N limited growth conditions was obtained (Fig. 2) by applying multipliers on the daily rainfall records for Lampung. The predicted maize yields, with or without trees, was highest for an annual rainfall of two-thirds of the actual record (2318 mm year^{-1}), with a rapid reduction for lower rainfall values and a gradual decline for higher rainfall (Fig. 2A). The presence of a hedgerow tree shifted the water limitation curve to the right (Fig. 2B), showing that even at an annual rainfall of 2000 mm 5-10% of the days in the cropping season water can be the growth limiting factor in the presence of hedgerows; it also shifted the nitrogen limitation curve to the left, indicating a positive effect on N supply of this (non-N_2 fixing) tree. N leaching is predicted to be reduced by the presence of hedgerow trees at all rainfall rates above 1000 mm year^{-1}, and the total filter efficiency increases (Fig. 2C and 2D). Filter effectiveness for the same tree and crop parameters decreases non-linearly with increasing rainfall, as the residence time of solutes in the deeper soil layers decreases non-linearly with a larger surplus of rainfall over evapotranspiration. Below an annual rainfall of 1000 mm year^{-1} the amount of water and N leaching into and out of the subsoil layer 4 (the deepest soil layer considered, 0.5 – 1 m depth) becomes negligible and the calculation of the filter function looses its meaning. The absolute increase of filter efficiency due to the presence of trees increases with decreasing rainfall from 9% at 1.4 times the rainfall (3260 mm year^{-1}) to 19% at 50% of the default rainfall (1160 mm year^{-1}), for the default crop and tree root length densities.

3.3 Safetynet Efficiency: Effect of Root Length Density and Distribution

A further WaNuLCAS model exploration of these effects at the default rainfall showed a strong dependence of filter functions in layer 4 (the deepest soil layer considered) on the tree root length density in this layer (Fig. 3). Filter functions for situations with hedgerow trees start to increase below the crop-only situation (maize is supposed to have a few roots in layer 4) if tree root length density exceeds a value of 0.001 cm cm^{-3}, and reaches a maximum when tree root length density in this layer becomes 1 cm cm^{-3} (Fig. 3B, note logarithmic scale). Tree biomass benefits from more roots in layer 4, but saturates at a tree root length density in layer 4 of 0.03 (Fig. 3C), as this apparently is sufficient to carry the tree through the dry season.

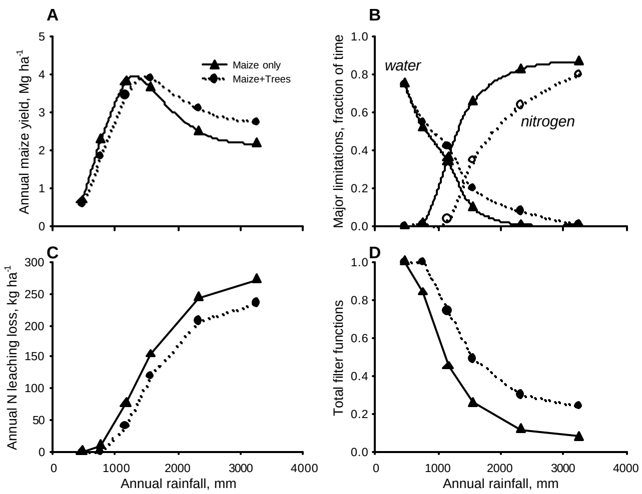

Figure 2. **A.** Model predictions of maize yield (2 crops per year; for a standard parameterization, see text) as a function of annual rainfall (obtained by using multipliers on the 1993 Lampung daily record – see arrow), with or without the presence of regularly pruned hedgerows of non-N-fixing trees; **B.** the fraction of the growing periods that either N or water is the main limiting factor (causing at least 10% reduction in growth on a given day and being the strongest current limitation); **C.** annual loss of N by leaching and lateral sub-surface flow; **D.** Overall filter efficiency for N, defined as uptake/(uptake + losses)

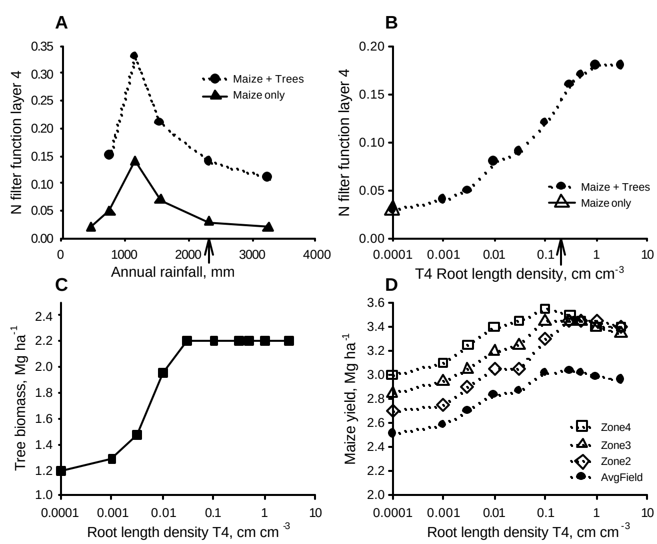

Figure 3. **A** and **B** Simulations of filter function [=uptake/(uptake+leaching)] for nitrogen of the fourth soil layer, A. as a function of annual rainfall and B. as function of tree root length density in layer 4 (N.B. logarithmic scale); **C** and **D** Tree biomass and maize yields in the same simulations.

In the predicted impacts of the hedgerow on the maize crop (Fig. 3D) the model predicts that a strong difference between crop zones exists for tree root length densities in layer 4 up to 0.1 cm cm^{-3}, and that higher tree root length densities in layer 4 actually benefit the crop, despite a higher biomass and thus stronger direct competition. The positive (safetynet functions) and negative (competition for water and N) impacts of simultaneous tree roots on maize yield was further analysed by separating relative tree root distribution from absolute root length density. Results for these calculations show (Fig. 4) that negative overall effects of the tree can be expected for trees that have all their roots in the topsoil, and for trees with only 0 – 10 % of their roots in the subsoil, at low overall tree root length. These same relative tree root distributions at higher total root length (i.e. higher absolute root lengths in both top and subsoil) can have a moderate positive effect on maize yield, while tree root systems with 20% or more of their roots in the subsoil were consistently positive for the crop, the higher total root length, the more positive the impact on maize.

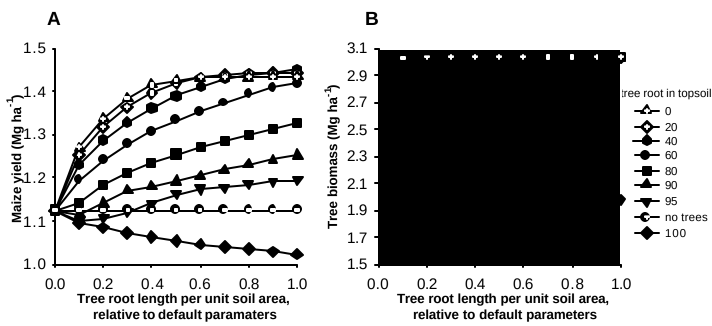

Figure 4. Predicted maize yield (**A**) and tree biomass (**B**) for the default rainfall situation of Figure 3 (2318 mm year-1), when relative distribution of tree roots with depth as well as total amount of tree roots are varied independently. Whereas the 'default' tree root system had 21.5 % of its roots in the top layer, a series of data was made that had 0 - 100% of its roots in the top layer and the remainder allocated to the deeper layers in proportion to the root length densities of the default case (the relative distribution over the four zones with increasing distance to the tree was not modified). For each of these root distributions, the total amount of roots was varied from 0.1 - 1 times the default, while maintaining the relative values.

A remarkable feature of these results is that at default values for total root length, the tree root systems with 60% of their roots below the topsoil led to (slightly) higher maize yields, than those with more (up to 100%) in the subsoil, while at lower total root system size the 100% in subsoil (0% in topsoil) was better for the maize. Although this effect is much too subtle to be recognized in any field data, it seems counter-intuitive. On detailed analysis the differences in crop N uptake between trees with 0 and 40% of their roots in the topsoil arise during dry spells in the cropping season when the sparse crop roots in the deeper soil layers have slightly more N available in situations where the trees forage partly in the topsoil.

Sensitivity analysis of the model thus shows that the tree root length density below the main crop root zone may have complex and partially unexpected effects on crop performance in situations where negative effects via competition for water and positive effects via improved N supply vary in intensity during the growing season. Positive effects of the trees via improved N supply would increase with time, and the current results averaged over 2 years (4 crops) are only a first indication of the overall impact of including hedgerow trees into the maize production system.

Apparently the tree root length density required for a safety-net function can be quite low, as it depends on the residence time of the mobile solute in the layer where the filter function is supposed to occur. For real trees the known root-length densities indicate that only a partial safety-net function can be expected to occur, as root length densities in the subsoil are normally less than 1 cm cm^{-3}, but above 0.001 cm cm^{-3}.

Overall, we conclude that filter functions for nitrogen on its way to leach out of the soil profile are related to rainfall, tree N demand and tree root length density in a strongly non-linear fashion. In formulating and using WaNuLCAS as mechanistic model for interactions in more complex agro-ecosystems, we quickly realize that parameters that can greatly influence the model outcome are insufficiently known. These parameters refer to the longer term replenishment of the nutrient pools accessed by deep-rooted trees or by plants with specific rhizosphere effects, as well as to the spatial correlation of roots or mycorrhizal hyphae of interacting plant species. For the performance of the system as a whole, however, management of the aboveground biomass and its effect on nutrient demand dominates the opportunities to make use of more complex agro-ecosystems to achieve a higher overall nutrient-use efficiency. The simulation model provides a framework for combining knowledge on component behaviour to system-level assessment of plant nutrition.

4. Challenges to Make It Work

Complexity of agro-ecosystems is no guarantee for avoiding excess nutrition problems. Filters are only effective, however, if they remain undersaturated. If the biomass from filterstrips is not regularly removed by harvesting, filter functions can only be expected for N and only through denitrification (or ammonia volatilization). Safetynets only function if there is unfulfilled demand -- they are thus not compatible with yield maximization of all system components, as supply is fluctuating with weather conditions, especially in systems with substantial organic reserves. The ecological analogue thus has clear limitations if close-to-maximum crop yields are expected. Where regular cutting or pruning of filter strips is needed to maintain their functionality, the biomass so obtained must have sufficient direct value to justify the labour use for the farmer.

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